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Driving Factors of Industrial Water Use Change Based on Carbon Emission and Sectoral Perspectives in Hebei Province, China

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Abstract: Hebei Province in China is facing a serious water shortage, which is further aggravated by the pressure of industrial transfer and the unreasonable structure of industrial water use. To explore the relationship between industrial water use and carbon emissions, in this study, a refined logarithmic mean divisia index (LMDI) decomposition method was developed to analyze the driving factors of industrial water use in Hebei Province during 2008–2019 from carbon emission and sectoral perspectives. The results show that the carbon emission effect, the water–carbon effect, and the industrial structure effect were the main factors contributing to the decrease in industrial water use during the study period. The carbon emission effect made a great contribution to its decline. The cumulative contributions of these factors were −1425, −533, and −763 million m^3 from 2008 to 2019. The contribution of the industrial structure effect was −106.93%, with a large potential for water saving. According to the sectoral analysis, the 32 sectors in Hebei Province exhibited significant sectoral heterogeneity, and the strong promoting industries were identified as the main sectors contributing to the increase in the promotion of industrial water use. This paper provides a reference for the scientific formulation of water-saving and emission-reduction policies and research on the water–carbon relationship in Hebei Province.

Keywords: LMDI; driving factors; industrial water use; carbon emission; sectoral analysis

1. Introduction

In recent years, the shortage of water resources has been prominent in Hebei Province. The per capita water resources of Hebei Province are 149.3 m^3, which is significantly less than the national per capita amount of 2062.9 m^3. It is one of the provinces with the most serious water resource problems in China. The average burial depth of the shallow groundwater increased from 9.32 m in 1986 to 18.18 m in 2019 [1]. The surface water is insufficient to support the production and domestic water demands, resulting in serious groundwater exploitation. The water resource issues in Hebei Province have been aggravated by agglomeration, urbanization, and population growth [2]. The water environment and water resources in Hebei Province are facing increasing pressure [3]. There are still many problems with industrial water use, mainly due to the disparity between the industrial structure and the water resource carrying capacity and the large gap in the water use efficiencies of the various sectors. In Hebei Province, the high water consumption industries accounted for more than 70% of the total industrial water use and more than 60% of the total industrial output value. Therefore, it is worth analyzing the driving mechanism of industrial water use and considering the inter-industry heterogeneity.

For the past few years, the government has permanently attached great importance to the issue of water resources. The central government has increased the intensity of

water diversion from the middle line of the South-to-North Water Diversion to Hebei Province. In 2018 and 2020, 2.24 and 3.65 billion m^3 of water was transferred to Hebei, respectively [4]. Although this effectively reduced the groundwater exploitation to a certain extent and relieved Hebei Province's water crisis, it was far from reversing the fundamental condition of the water shortage. Hebei Province also formulated a series of policies. In 2019, the government formulated the Beijing–Tianjin–Hebei Industrial Water-Saving Action Plan, which required the water use per 10,000 yuan of industrial added value in the Beijing–Tianjin–Hebei region to be less than 10.3 m^3. However, in Hebei Province it was 15.7 m^3. In addition, compared with the water intensity control target in the 14th Five-Year Plan [5], the industrial water efficiency in Hebei Province was still 16.20% short of the target. Based on the water issues in Hebei Province, many studies have been conducted. Zheng et al. [6] found that industrial distribution had a greater impact on the groundwater extraction. In addition, many studies on the relationship between industrial water use and the economy and industrial restructuring have been conducted [7,8]. Liu et al. [9] showed that industrial restructuring was beneficial to improving water and energy efficiency. Wu et al. [7] found that the correlation between the added industrial value and the industrial water use was poor. However, these studies were more biased toward overall industry analysis, downplaying the impact of the internal structure, especially the impact of the industrial structure on water use. Therefore, in this study, we further analyzed the driving mechanisms of the industrial water use changes from the sectoral perspective.

To date, many scholars have conducted extensive research on the driving mechanisms of industrial water use changes [10,11]. First, in terms of the research content, more studies have focused on the relationship between water use and economic development, the industrial structure, and technological progress [12,13]. Zhang et al. [14] explored the effects of the economic scale, industrial structure, and water use efficiency on industrial water use in Tianjin. Lu et al. [15] quantitatively analyzed the factors influencing water use change and found that technology and economic development were the main factors. Long et al. [16] argued that the intensity effect reduced water resource consumption. Yang and Chen [17] concluded that structural and technological factors inhibited the growth of water consumption. Compared with previous studies, Wang et al. [18] took environmental protection factors into consideration. Several scholars also explored the relationship between water resource utilization and energy consumption [19,20] and carbon emissions [21]. Zhao et al. [22] studied the water–soil–energy–carbon relationship, and their results showed that the economic output of water resources can contribute to carbon emissions. Babel et al. [23] found a significant positive correlation between water and carbon emissions in the automotive manufacturing industry. Considering the double carbon target proposed by China, Hebei Province, as an important part of the capital economic circle, is bound to respond positively and achieve carbon peaking and carbon neutrality. With the implementation of the carbon emission policy, the change in the carbon emissions will also affect the change in the industrial water use in Hebei Province. Second, in terms of research methods, the linear regression method [23], gray correlation analysis method [14], structural decomposition method (SDA) [24], and logarithmic mean divisia index method (LMDI) [25] have been more often used to analyze the factors influencing water use changes and carbon emissions. By contrast, the SDA method and LMDI method can quantify the degree of the influences among the factors. However, the LMDI method has no residuals, good decomposition, and strong adaptability. Moreover, it can dynamically analyze the changes in different periods. Zhang et al. [25] used the LMDI method to analyze the drivers of agricultural water use in the middle reaches of the Heihe River during different periods. Wu et al. [26] analyzed the drivers of water consumption in the Xinjiang Uygur Autonomous Region. In addition, this method has been widely applied in the field of water resources and carbon emissions in recent years [27]. This method can examine the direction and extent of each driver's effect on the overall goal. Therefore, in this study, the LMDI method was used to dynamically analyze the changes in the industrial water use and its drivers in Hebei Province.

According to previous studies, the main factors affecting industrial water use can be summarized as industrial economic growth, industrial structure, and industrial water efficiency; however, the impact of carbon emissions on industrial water use has been less quantitatively studied. Previous research on industrial water use changes was mainly based on analysis from the perspective of individual industries or sectors. The industry classification was rough and could not fully reflect the changes in the water use in the internal sectors. The contributions of this study are as follows. First, the LMDI method was chosen to analyze the driving factors of industrial water use in Hebei Province from 2008 to 2019, avoiding the influence of the residual values, making the results more accurate, and enriching the literature on the drivers of industrial water use. Second, the industrial sub-sector perspective was examined, focusing on the industry differences of industrial water use changes. Third, the traditional LMDI method was refined, carbon emission factors were introduced, and the impact of carbon emissions on industrial water use was quantitatively analyzed. Therefore, in this study, the industrial sectors were taken as the entry point and carbon factors were introduced based on the traditional LMDI method to analyze the driving factors of industrial water use in Hebei Province from 2008 to 2019. We aimed to provide basic support and a reference for subsequent studies in Hebei Province and even other regions, as well as for the formulation of industrial water conservation and carbon reduction policies.

2. Materials and Methods

2.1. Basic Method

The LMDI method is an effective method for analyzing the mechanism of resource utilization. It is fully decomposable, has no residual term, and can effectively solve the zero values problem [26]. In addition, it has a wide applicability. According to the study of Ang [28], we assumed that V is the decomposition variable in the study, denoted as $V_1, V_2, \cdots, V_n$; there are n influencing factors, $x_1, x_2, \cdots, x_n$. The subscript i denotes the subcategory of the set in which the structural changes are studied. t represents the time variable:

$$V^t = \sum_i V_i^t = \sum_i x_{1,i}^t x_{2,i}^t \cdots x_{n,i}^t. \tag{1}$$

We considered each factor as a function of t. Then, V is also a function of t, and

$$\frac{dV^t}{dt} = \sum_k \sum_i x_{1,i}^t x_{2,i}^t \cdots x_{k-1,i}^t \frac{dx_{k,i}^t}{dt} = \sum_k \sum_i V_i^t \frac{dx_{k,i}^t}{dt}. \tag{2}$$

The above equation integrates both sides of the time simultaneously. Then, the total variation is obtained as follows:

$$\Delta V = V^t - V^0 = \int_0^t \frac{dV}{dt} dt = \sum_k \int_0^t \sum_i V_i^t \frac{d\ln(x_{k,i}^t)}{dt} dt, \tag{3}$$

$$\Delta V_{x_k} = \int_0^t \sum_i V_i^t \frac{d\ln(x_{k,i}^t)}{dt} dt. \tag{4}$$

Finally, according to the integral median value theorem and the additive decomposition model [28], the following equations are obtained:

$$\Delta V_{x_k} = \sum_i \frac{V_i^t - V_i^0}{\ln V_i^t - \ln V_i^0} \ln\left(\frac{x_{k,i}^t}{x_{k,i}^0}\right). \tag{5}$$

$$\Delta V = \sum_k \Delta V_{x_k}. \tag{6}$$

On the left side of the equation, ΔV represents the total variation, while on the right side of the equation, it represents the impact associated with each factor in Equation (1). ΔV_{x_k} is the variation caused by x_k.

2.2. Refined LMDI Method

Industrial water use is usually decomposed into three factors: the economic scale, structure, and water use efficiency [29,30]. There is also a significant positive correlation between energy consumption and water use [31]. Carbon emissions are closely linked to energy. By inference, there is a significant relationship between carbon emissions and water use. Therefore, in this study, the water–carbon relationship factor and carbon emission efficiency were introduced on the basis of the traditional LMDI decomposition method.

First, the total industrial water use can be decomposed as follows:

$$W^t = \sum_{i=1}^{n} W_i^t = \sum_{i=1}^{n} \frac{W_i^t}{N_i^t} \times \frac{N_i^t}{E_i^t} \times \frac{E_i^t}{E^t} \times E^t = \sum_{i=1}^{n} R_i^t \times C_i^t \times S_i^t \times E^t \tag{7}$$

where W^t is the total industrial water use in year t; W_i^t is the industrial water use of sector i in year t; N_i^t is the carbon emissions of sector i in year t; E_i^t is the industrial output value of sector i in year t; E^t is the total industrial output in year t, that is, the economic scale; and S_i^t represents the proportion of the sector i in year t to the total industrial output value, that is, the industrial structure. R_i^t is the water use per ton of carbon emissions in sector i, that is, the water–carbon nexus. C_i^t is the carbon emissions per 10,000 yuan of industrial output value in sector i, that is, the carbon emission efficiency.

According to its additive model [28], the change in industrial water use from years 0 to t can be rewritten as follows:

$$\Delta W = W^t - W^0 = \Delta W_R + \Delta W_C + \Delta W_S + \Delta W_E \tag{8}$$

in which,

$$\Delta W_R = \sum_{i=1}^{n} L_i^t \times \ln \frac{R_i^t}{R_i^0}, \tag{9}$$

$$\Delta W_C = \sum_{i=1}^{n} L_i^t \times \ln \frac{C_i^t}{C_i^0}, \tag{10}$$

$$\Delta W_S = \sum_{i=1}^{n} L_i^t \times \ln \frac{S_i^t}{S_i^0}, \tag{11}$$

$$\Delta W_E = \sum_{i=1}^{n} L_i^t \times \ln \frac{E^t}{E^0}, \tag{12}$$

$$L_i^t = \begin{cases} \frac{W_i^t - W_i^0}{\ln W_i^t - \ln W_i^0}, & W_i^t \neq W_i^0 \\ W_i^t, & W_i^t = W_i^0 \neq 0 \\ 0, & W_i^t = W_i^0 = 0 \end{cases} \cdot \tag{13}$$

In Equations (8)–(13), ΔW is the total change in the industrial water use between year 0 and year t, that is, the economic scale effect; ΔW_R is the change in the industrial water use caused by the water–carbon nexus, that is, the water–carbon effect; ΔW_C is the change in the industrial water use caused by improving the carbon emission efficiency, that is, the carbon emission effect; ΔW_E is the change in the industrial water use caused by changes in the industrial economic scale, that is, the economic scale effect; and ΔW_S is the change in the industrial water use caused by adjusting the industrial structure, that is, the industrial structure effect. For each of the above decomposition effects, if the value is positive, the factors promote industrial water use; otherwise, the effect inhibits industrial water use.

To measure the effects of the various factors on the changes in industrial water use from both the total industry and sectoral perspectives, the degrees of the contributions of the various factors were calculated according to the change in industrial water use. The equation [19] can be written as follows:

$$\rho_E = \frac{\Delta W_E}{|\Delta W|}. \tag{14}$$

If the contribution rate $\rho_E > 0$, the economic scale effect has an incremental driving effect; otherwise, it has a detrimental driving effect. The contribution rates of the driving factors are similar. The higher the absolute value of the contribution rate, the greater the relative degree of the influence, and vice versa.

2.3. Industrial Carbon Emissions

In this study, we estimated the fossil fuel-related CO_2 emissions by energy type. The CO_2 emissions were accounted for using the following formula:

$$N_i = \sum_{k=1}^{m} CE_{ik} = \sum_{k=1}^{m} E_{ik} \times \eta_k \tag{15}$$

where k denotes the different fossil fuels; E_{ik} denotes the consumption of fuel k in sector i; η_k is the CO_2 emission coefficient of fossil fuel k; CE_{ik} is the carbon emission of fossil fuel k in sector i; and N_i is the carbon emission of sector i.

2.4. Data

In this study, due to the data availability and accessibility, the water use data for each sector was limited. The study period was from 2008 to 2019. Based on China's National Industry Classification standard of the National Bureau of Statistics, the industry in Hebei Province was divided into 32 sectors based on the appropriate merging of some industry sectors (Table 1). The data were all collected from the *Hebei Statistical Yearbook (2009–2020)*, *China Water Resources Bulletin*, *Hebei Province Water Resources Bulletin*, and *Hebei Province Economic Census Yearbook for 2008*. To avoid the influence of price factors, the output value data for the various industries were converted into constant prices in 2008. In this study, the carbon emission coefficient method was used to estimate industrial carbon emissions. Due to data limitations, we considered only 14 major energy sources, namely, coal, coke, coke oven gas, other gases, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, natural gas, other coking products, and other petroleum products. The relevant data and parameters were obtained from *China Energy Statistical Yearbook (2009–2020)*, *Hebei Statistical Yearbook (2009–2020)*, and the IPPC [32]. According to the data in the *Hebei Statistical Yearbook (2009–2020)*, we classified the industries with high water consumptions and low water use efficiencies as high water consumption industries, while the remaining industries were classified as general industries. There were 15 main industries with high water use, namely A1, A3, A6, A7, A8, A10, A13, A16, A17, A19, A20, A21, A22, A31, and A32. In addition, based on the size of the carbon emissions, the top six industries with the largest carbon emissions were defined as the high carbon industries. The high carbon industries mainly included A1, A16, A17, A21, A22, and A31.

Table 1. Industrial sectors and their codes in Hebei Province.

Code	Sector	Code	Sector
A1	Coal mining and washing	A17	Chemical raw materials and chemical products manufacturing
A2	Oil and gas exploration	A18	Pharmaceutical manufacturing
A3	Ferrous metal mining	A19	Chemical fiber manufacturing
A4	Non-ferrous metal mining	A20	Rubber and plastic products

Table 1. *Cont.*

Code	Sector	Code	Sector
A5	Non-metallic mining and processing	A21	Non-metallic mineral products
A6	Agro-food processing	A22	Ferrous metal smelting and rolling processing
A7	Food manufacturing	A23	Non-ferrous metal smelting and rolling processing
A8	Wine, beverage, and refined tea manufacturing	A24	Metal products
A9	Tobacco	A25	General equipment manufacturing
A10	Textiles	A26	Specialized equipment manufacturing
A11	Wood processing	A27	Transportation equipment manufacturing
A12	Furniture manufacturing	A28	Electrical machinery and equipment manufacturing
A13	Paper and paper products	A29	Computer, communication, and other electronic equipment manufacturing
A14	Printing and reproduction of recording media	A30	Other
A15	Cultural, educational, and sporting goods manufacturing	A31	Production and supply of electric power and heat power
A16	Petroleum processing, coking, and nuclear fuel processing	A32	Gas production and supply

3. Case Study

3.1. Industrial Water Use and Carbon Emissions

As shown in Figure 1, Hebei Province (113°27′–119°50′ E, 36°05′–42°40′ N) is bordered by the Bohai Sea to the east and is surrounded by Beijing and Tianjin, with a total area of 188,500 km^2. Although it contains less than 1% of the water resources, Hebei Province supports 5.42% of the country's population and produces 3.54% of the gross domestic product (GDP). The groundwater resource's water supply in Hebei Province was 9644 million m^3, accounting for 52.9% of the total water supply. About 60% of the water supply was used for agriculture, with about half from the groundwater supply [33]. Hebei's industrial and agricultural water largely depend on external water transfer and groundwater. The cumulative amount of groundwater overdraft in the province was as high as 150 billion m^3, and the overdraft time of the groundwater was long. This seriously threatened the security of the water supply [34]. Therefore, Hebei Province relies heavily on external water transfer and groundwater for its social and economic development, resulting in serious groundwater overexploitation in this region.
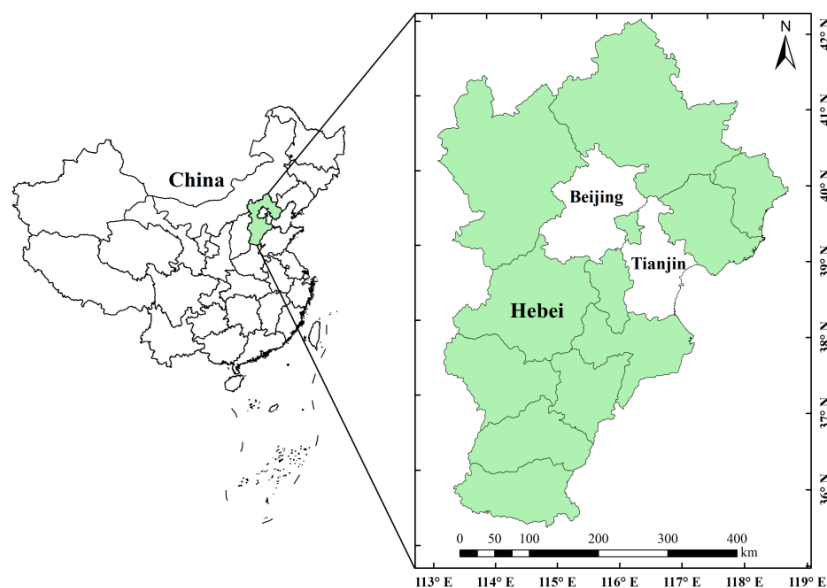
Figure 1. Geographic location of Hebei Province in China.

Figure 2 shows the trend of the industrial water use and industrial output value in Hebei Province. During 2008–2019, the total industrial output value increased rapidly and was 1.8 times higher in 2019 compared with 2008, with an average annual growth rate of 9.75%. Figure 3 illustrates the trend of the industrial carbon emissions in Hebei Province. The industrial carbon emissions increased, with an average annual growth rate of 3.76%.
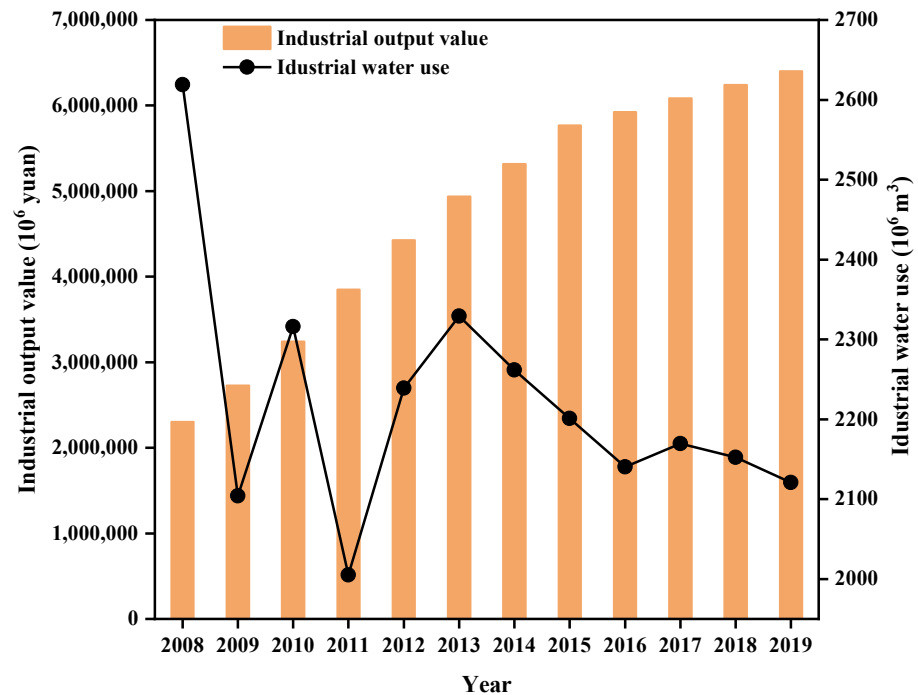
Figure 2. The trends of the industrial water use and industrial output value in Hebei Province.
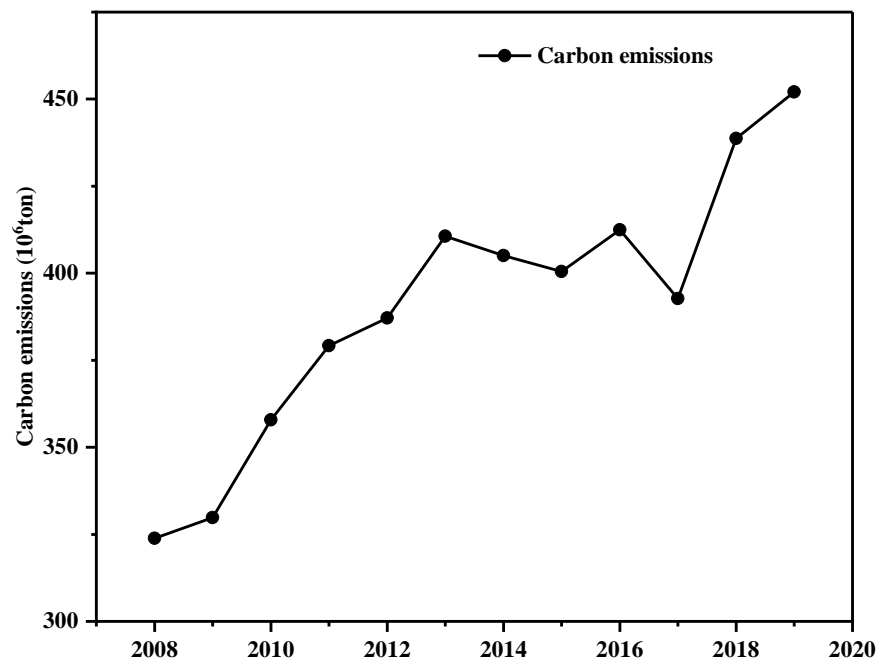
Figure 3. The total industrial carbon emissions.

3.2. Statistical Analysis of Sectors

There were large differences in the water use among the different industrial sectors, and the industries with high water consumption accounted for a large proportion of the industries in Hebei Province (Figures 4 and 5). The water use of the high water consumption

industries accounted for 75.55% of the total industrial water use. The ferrous metal smelting and rolling processing sector (A22) accounted for the largest proportion of the water use, up to 29%. The industrial output value of the high water consumption industries accounted for 64.83% of the total industrial output value. The ferrous metal smelting and rolling processing sector (A22) was a high water consumption industry, and its output value accounted for the largest proportion, reaching 26%.
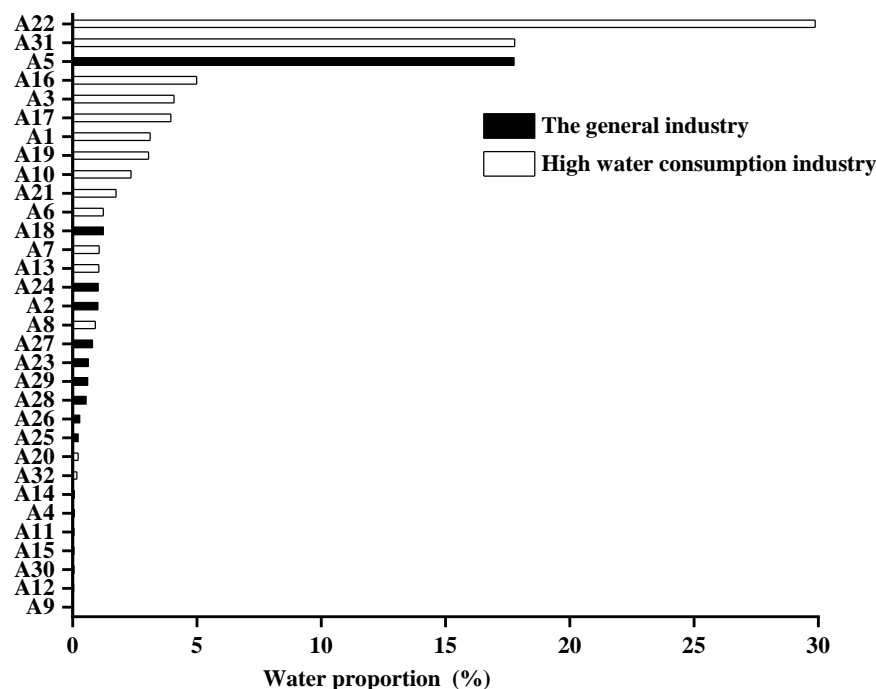
Figure 4. Proportions of water use by industrial sectors in Hebei Province.
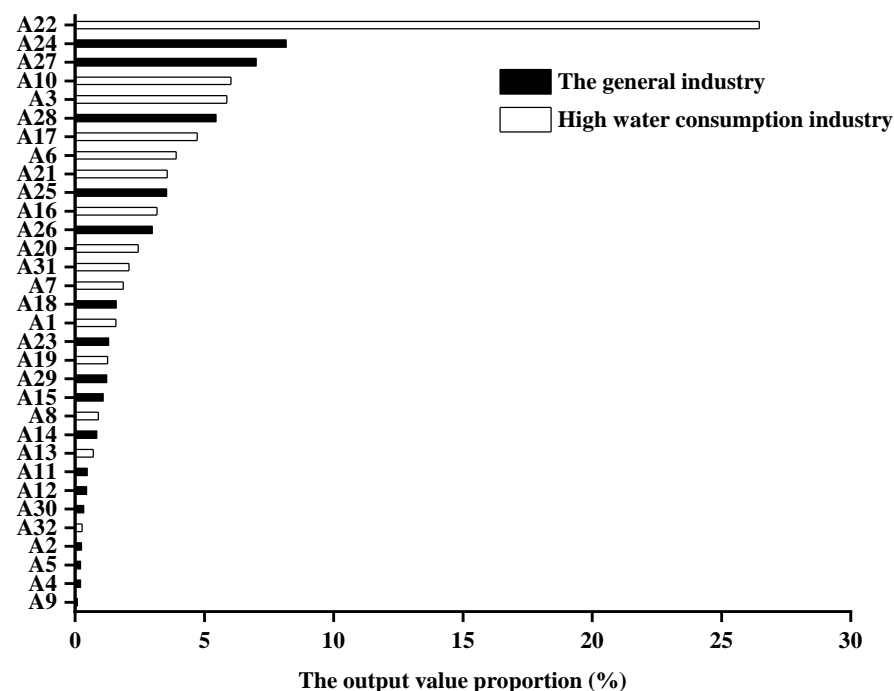
Figure 5. Proportions of output value by industrial sectors in Hebei Province.

As shown in Figure 6, although the water use efficiency of each industry improved considerably during the study period, the gap in the water efficiency among sectors was still large. The water intensity of the non-metallic mining and processing sector (A5)

exceeded 100 times that of the computer, communication, and other electronic equipment manufacturing sector (A29) and was 23 times higher than the average water intensity of the various sectors. The water intensity of the non-metallic mining and processing sector (A5) was 38 times lower than that in Tianjin. In addition, Hebei Province exhibited a large gap in water use efficiency compared with Beijing and Tianjin. For example, the water efficiency of the production and supply of electric power and heat power sector (A31) was 23 times lower than that in Beijing and 2.5 times lower than that in Tianjin. The ferrous metal smelting and rolling processing sector (A22) was 1.73 times lower than that in Beijing, but similar to Tianjin. These results reflect the unbalanced industrial water use efficiency of the various sectors in Hebei Province, and it is still necessary to further improve the water use efficiencies of the various industries.
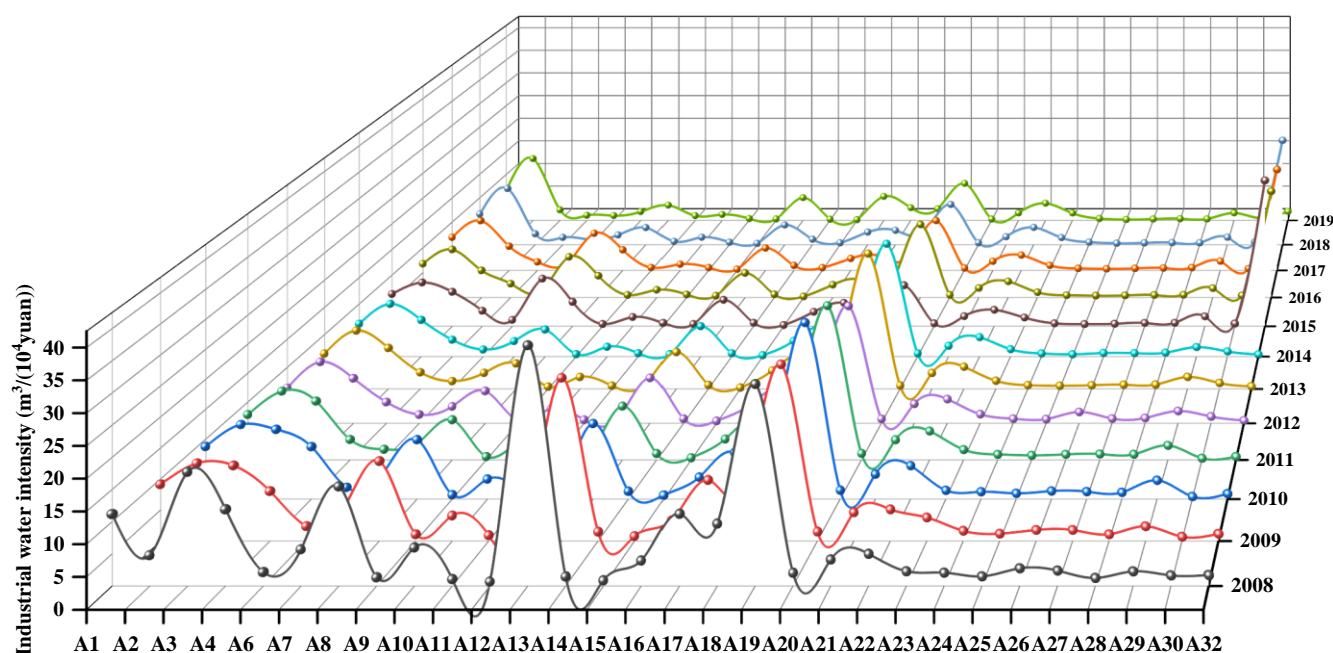

Figure 6. Water intensity of industrial sectors in Hebei Province.

4. Results and Analysis

4.1. Overall Decomposition Analysis

In this study, the change in the industrial water use in Hebei Province from 2008 to 2019 was decomposed into the economic scale effect, industrial structure effect, water–carbon effect, and carbon emission effect according to the above formula. Figure 7 illustrates the decomposition results.

Analyzed in terms of the cumulative effect, the carbon emission efficiency played a key role in reducing industrial water use, with a cumulative reduction of 1425 million m^3, accounting for −286.11%. The water–carbon effect and the industrial structure effect had the next highest effects, with reductions of 763 and 533 million m^3, respectively. The contribution rates of these two effects were −153.19% and −106.93%, respectively. The cumulative reduction in the industrial water use was greater than the increase in the economic effect, resulting in a reduction in industrial water use in Hebei Province. Except for a few years, the water–carbon effect, the industrial structure effect, and the carbon emission effect were negative, indicating that these factors had a negative driving effect on the growth of the industrial water use. The economic scale effect was always positive, indicating that the economic scale effect promoted the growth of industrial water use.

According to the multi-year time scale analysis, the economic effect during 2008–2011 and 2016–2019 was 1143 and 163 million m^3, respectively, with a diminishing role in promoting industrial water growth. Based on the annual time scale analysis, the industrial water use was stimulated with an average annual increase of 205 million m^3 due to the

economic scale effect. The industrial water use growth in 2009–2010, 2011–2012, and 2012–2013 was determined, and the economic effect dominated the growth of industrial water use during these periods. Analysis of the multi-year time scale revealed that during 2008–2011 to 2016–2019, the industrial structure effect was −86 and −285 million m^3, respectively. As for the absolute value of the contribution rate, it exhibited an increasing trend, indicating that the industrial structure effect gradually strengthened the inhibition effect of the industrial water use. However, the contribution of the industrial structure effect was smaller than those of the carbon emission effect and the water–carbon effect. Before 2014, the water-saving effect of the industrial structure effect was not obvious, and the carbon emission effect and the water–carbon effect were dominant. After 2014, the water-saving capacity of the industrial structure effect began to emerge.
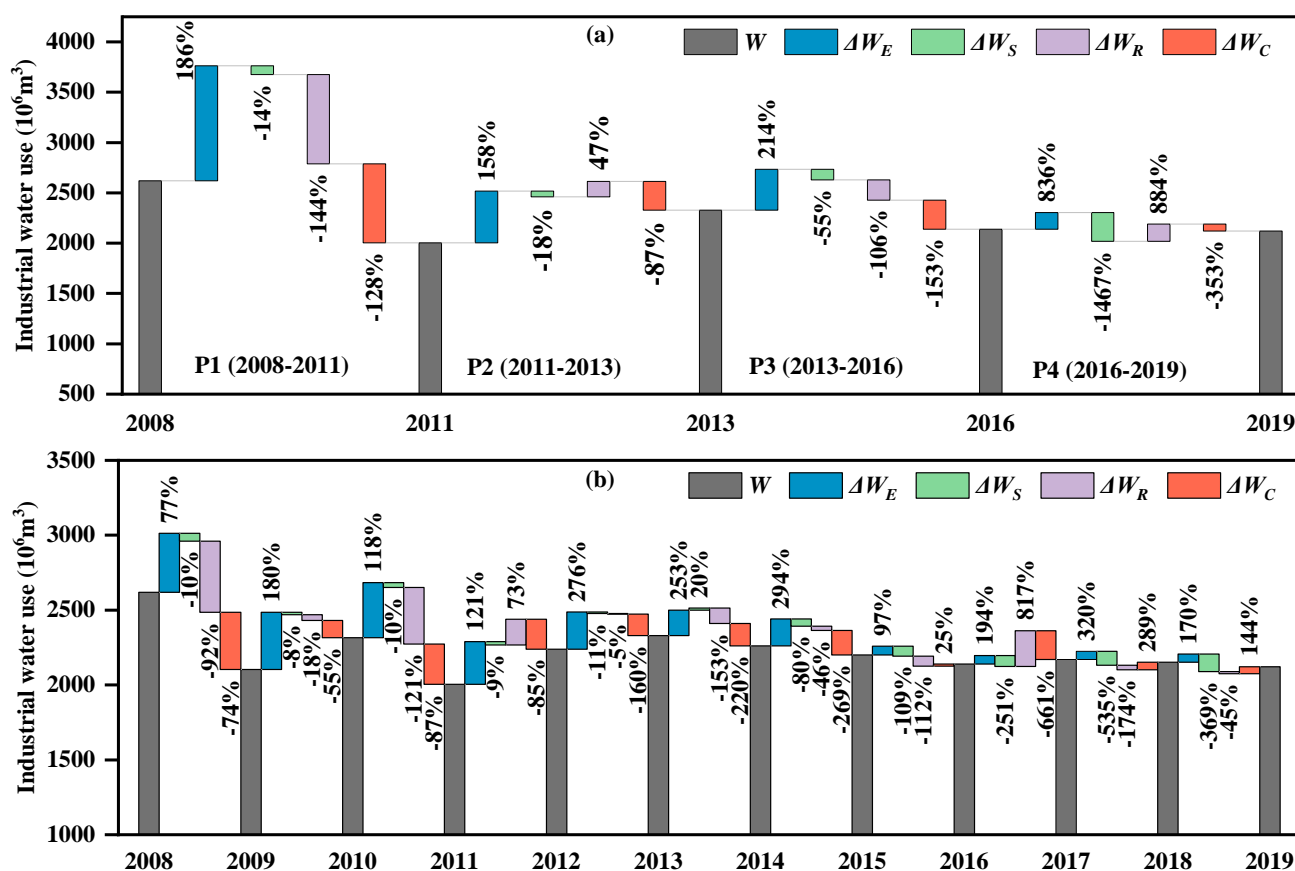
Figure 7. Contribution of each driving factor to the change in the industrial water use in Hebei Province during 2008–2019 on (**a**) the multi-year time scale; and (**b**) the annual time scale.

In 2008–2009, the water–carbon effect was reduced by 476 million m^3, which was nine times the industrial structure effect. This result indicates that the water–carbon relationship was coordinated and was more effective in reducing industrial water use. The water–carbon relationship deteriorated, resulting in a decrease in water savings from 887 million m^3 in 2008–2011 to 201 million m^3 in 2013–2016. The water savings decreased significantly by about 77%, and the carbon emission effect decreased from 785 to 69 million m^3. The change in the water reduction reflected the diminishing roles of the water–carbon effect and the carbon-emission effect in curbing the growth of industrial water use. The dampening effect of the carbon emissions effect also reflects the significant dampening effect of technological progress on industrial water use. In addition, the sum of the water–carbon effect and the carbon emission effect reflects the impact of the industrial water use efficiency. The sum of these two effects gradually changed from a negative to a positive value, indicating that increasing water use efficiency can significantly reduce

water use. However, due to the limitations of technological development, technological advancements cannot infinitely enhance water use efficiency [30].

4.2. Sectoral Decomposition Analysis

4.2.1. Total Effect

To obtain a better understanding of the features of the water use throughout the total industry, the factors influencing the water use were examined from the sector perspective. Figures 8 and 9 present the findings of the factor decomposition for each industrial sector in the analysis.
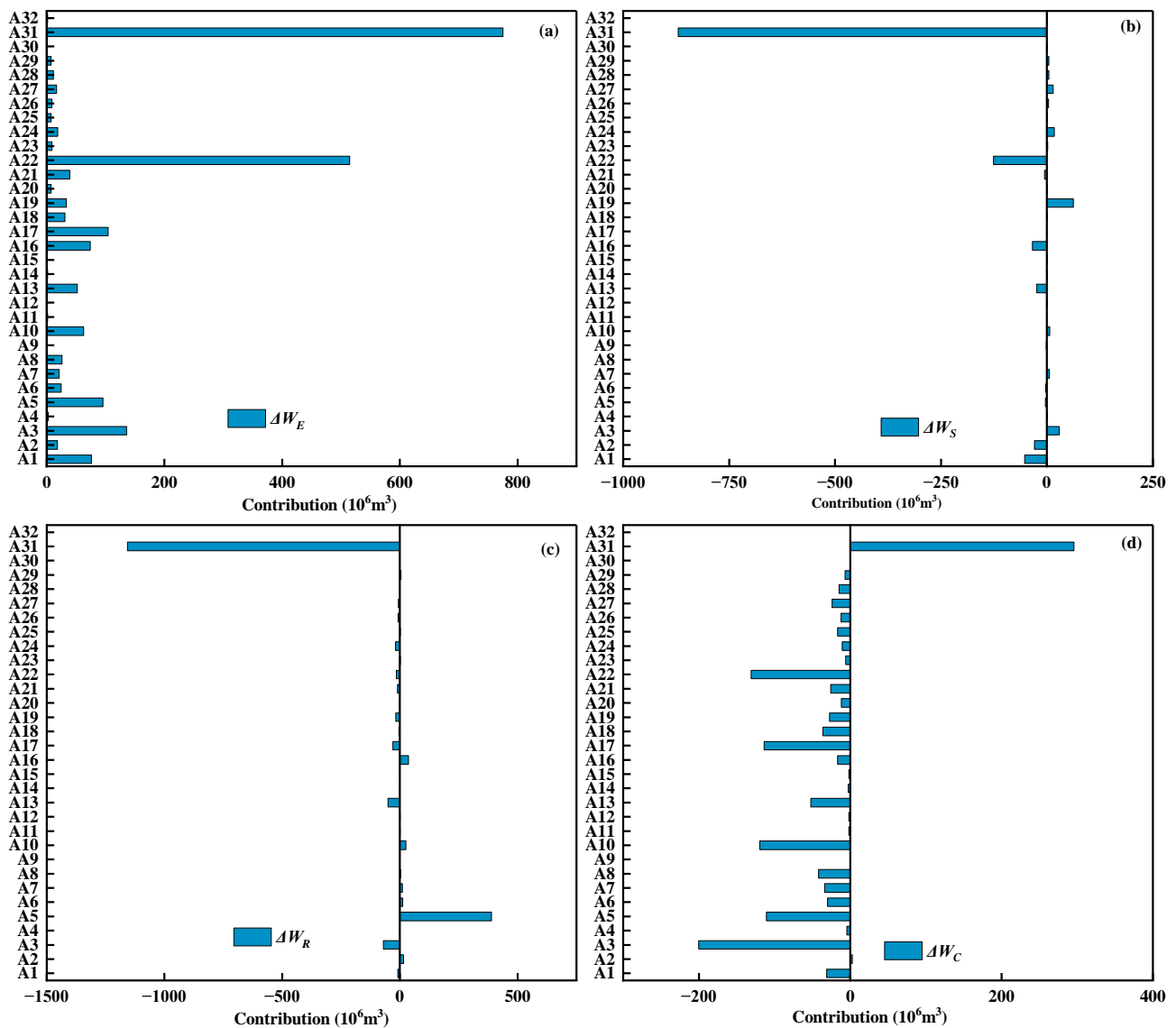
Figure 8. Decomposition results of industrial sectors during 2008–2019. ((**a**) economic scale effect; (**b**) industrial structure effect; (**c**) water–carbon effect; and (**d**) carbon emission effect).

In terms of the total effect of the industrial sectors, 15 sectors in Hebei Province were negative from 2008 to 2019, of which nine were high water consumption industries. The production and supply of the electric power and heat power sector (A31) and the ferrous metal mining sector (A3) made the largest contributions to the reduction in water use, with contributions of −192.13% and −21.38%, respectively. The total effect of 17 sectors was positive, of which six were high water consumption industries. The non-metallic mining and processing sector (A5) and the ferrous metal smelting and rolling processing sector

(A22) were the main industries that promoted the increase in water use, with contributions of 74.17% and 48.50%, respectively. These findings show that in recent years, the industrial structure of Hebei Province has gradually shifted to low water consumption industries. The proportion of water use in most traditional high water consumption industries has decreased, but the proportion of water use in some traditional industries still increased, such as A6 and A7. This was significantly related to the developed agriculture and the heavy industrial structure, and it also indirectly reflects the strong dependence of industrial development on agriculture in Hebei Province [11].

	ΔW_E	ΔW_S	ΔW_R	ΔW_C	ΔW
A32	0.07	0.12	-0.08	0.11	0.59
A31	35.57	-87.49	-128.81	37.73	-192.13
A30	0.03	0.09	-0.07	0	0.15
A29	0.33	0.44	0.46	-0.84	1.86
A28	0.52	0.44	-0.02	-1.86	0.18
A27	0.76	1.48	-0.68	-3.05	0.26
A26	0.41	0.37	-0.8	-1.52	-1.3
A25	0.35	0.08	0.22	-2.13	-1.27
A24	0.85	1.75	-2.08	-1.33	1.39
A23	0.42	0.19	0.29	-0.75	1.55
A22	23.62	-12.71	-1.74	-16.7	48.5
A21	1.79	-0.58	-1.12	-3.28	-0.5
A20	0.33	0.11	-0.2	-1.48	-1.03
A19	1.53	6.24	-1.91	-3.48	10.24
A18	1.42	0.08	-0.46	-4.62	-1.75
A17	4.8	-0.09	-3.29	-14.49	-7.94
A16	3.38	-3.42	4.06	-2.13	11.93
A15	0.04	0.11	0.01	-0.21	0.1
A14	0.07	0.11	0.02	-0.32	0.04
A13	2.39	-2.4	-5.64	-6.66	-14.98
A12	0.03	0.02	0.13	-0.22	0.07
A11	0.06	-0.02	0.05	-0.22	-0.03
A10	2.88	0.64	2.79	-15.25	-5.06
A9	0.04	-0.13	-0.01	-0.02	-0.13
A8	1.19	-0.02	0.31	-5.34	-2.69
A7	0.97	0.57	1.23	-4.3	0.81
A6	1.13	-0.33	1.37	-3.83	0.77
A5	4.37	-0.38	43.25	-14.13	74.17
A4	0.11	0.1	-0.16	-0.55	-0.46
A3	6.23	2.88	-7.86	-25.55	-21.38
A2	0.83	-2.97	1.72	0.36	1.37
A1	3.48	-5.28	-0.99	-3.96	-3.36

Rate (%): 75.00 — 21.40 — −32.20 — −85.80 — −139.4 — −193.0

Figure 9. Changes in the contribution rates of the factors in the industrial sectors during 2008–2019.

4.2.2. Economic Scale Effect

Figures 10 and 11 show that the expansion of the economic scale in the different periods in each sector promoted the growth of industrial water use. The influence of the economic scale on industrial water use weakened in the production and supply of electric power and heat power sector (A31) (down from 37.36% to 16.75%), the ferrous metal mining sector (A3) (down from 9.54% to 6.38%), and the chemical raw materials and chemical products manufacturing sector (A17) (down from 5.43% to 4.34%). These findings indicate that the water conservation policy issued by Hebei Province has restricted the scale expansion of these industries, causing the impact of their expansion on water use to gradually weaken. However, the contribution to the industrial water use increased in the non-metallic mining and processing sector (A5) (up from 0.42% to 16.39%), the chemical fiber manufacturing sector (A19) (up from 0.62% to 2.42%), and the ferrous metal smelting and rolling processing sector (A22) (up from 21.92% to 29.46%). This indicates that the economic expansion of these industries, especially the high water-consuming industries, promoted the growth of water use and was not conducive to water conservation. The contributions of the economic effects of the remaining industries only changed slightly. This indicates that there were obvious differences in the economic effects of the various

industries. Limiting the scale expansion of the major water-consuming industries can effectively reduce industrial water use. In particular, the economic scale effect increased the industrial water use the most significantly in the production and supply of electric power and heat power sector (A31) and the ferrous metal smelting and rolling processing sector (A22). During the study period, the economic effects of these two sectors drove average increases in the water use of 153.09 and 141.97 million m^3, respectively. Their contributions were 27.54% and 25.54%, respectively. These two industries were also the two industries with the greatest impact on the economic effect, exhibiting high water consumption characteristics.
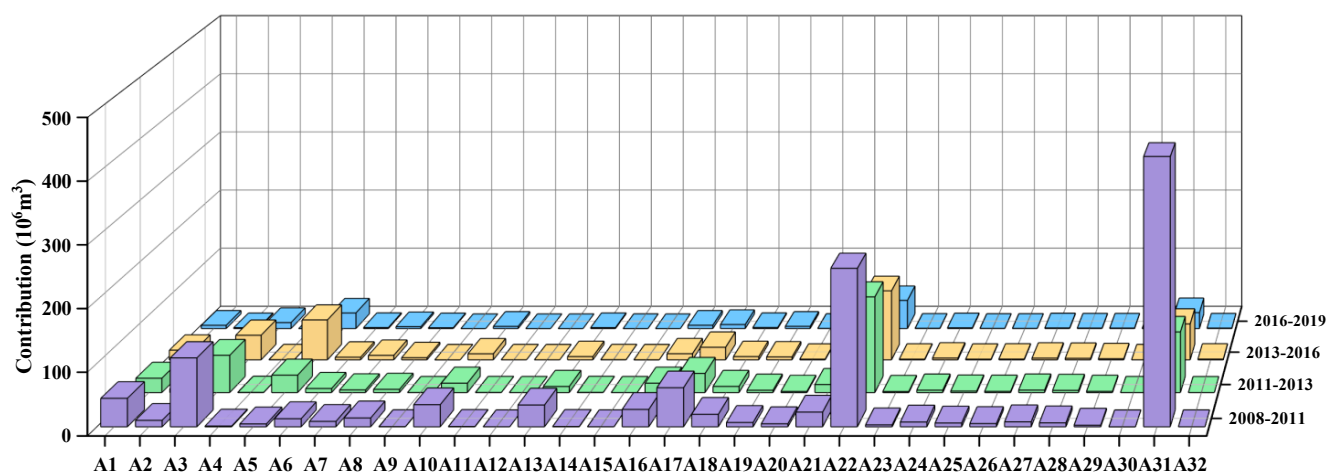

Figure 10. Economic scale effects of changes in water use by sector.

4.2.3. Industrial Structure Effect

Figures 11 and 12 show that the industrial structure effect was unstable, and proper industrial restructuring can achieve a better water-saving effect. During 2008–2011, 15 sectors were affected by the industrial restructuring, and their structural effects had a dampening effect on the growth of the industrial water use. The production and supply of electric power and heat power sector (A31) had the greatest inhibitory effect, reducing water use by 69.91 million m^3, with a contribution of −81.49%. The primary industries that contributed to the growth of the industrial water use were the ferrous metal mining sector (A3), with an increase of 49.51 million m^3 and a contribution of 57.71%. During 2011–2013, 13 sectors had negative structural effects. The production and supply of electric and heat power sector (A31) still had the largest inhibitory effect, with a contribution of −106.87%. However, two sectors (A22 and A17) changed from inhibition to promotion, and their contribution rates changing from −50.48% to 30.47% and from −14.22% to 18.25%, respectively. During 2013–2016, the structural effects acted as a damper in 16 sectors. After 2013, the production and supply of electricity power and heat power sector (A31) remained the most influential. The chemical fiber manufacturing sector (A19) gradually become the main industry in which structural factors inhibited the growth of the industrial water use.

Overall, the industrial structure effects of the different sectors on the water use growth varied over time. The high water consumption industries were the objects of long-term critical industrial adjustment. Most of the industrial structure effects during the different periods were negative, exhibiting an excellent water-saving effect. In particular, the relatively high proportion of water reduction in the production and supply of electricity and heat power sector (A31) indicates that its industrial restructuring achieved a good result. However, the industrial structure effect of these sectors (A5, A10, and A17) exhibited greater fluctuations, alternating between promoting and inhibiting the water-saving effect. In addition, according to the contribution of each sector during 2016–2019, the contribution of the industrial structure effect to the overall structural effect was low in all industries, except for A31 and A22.
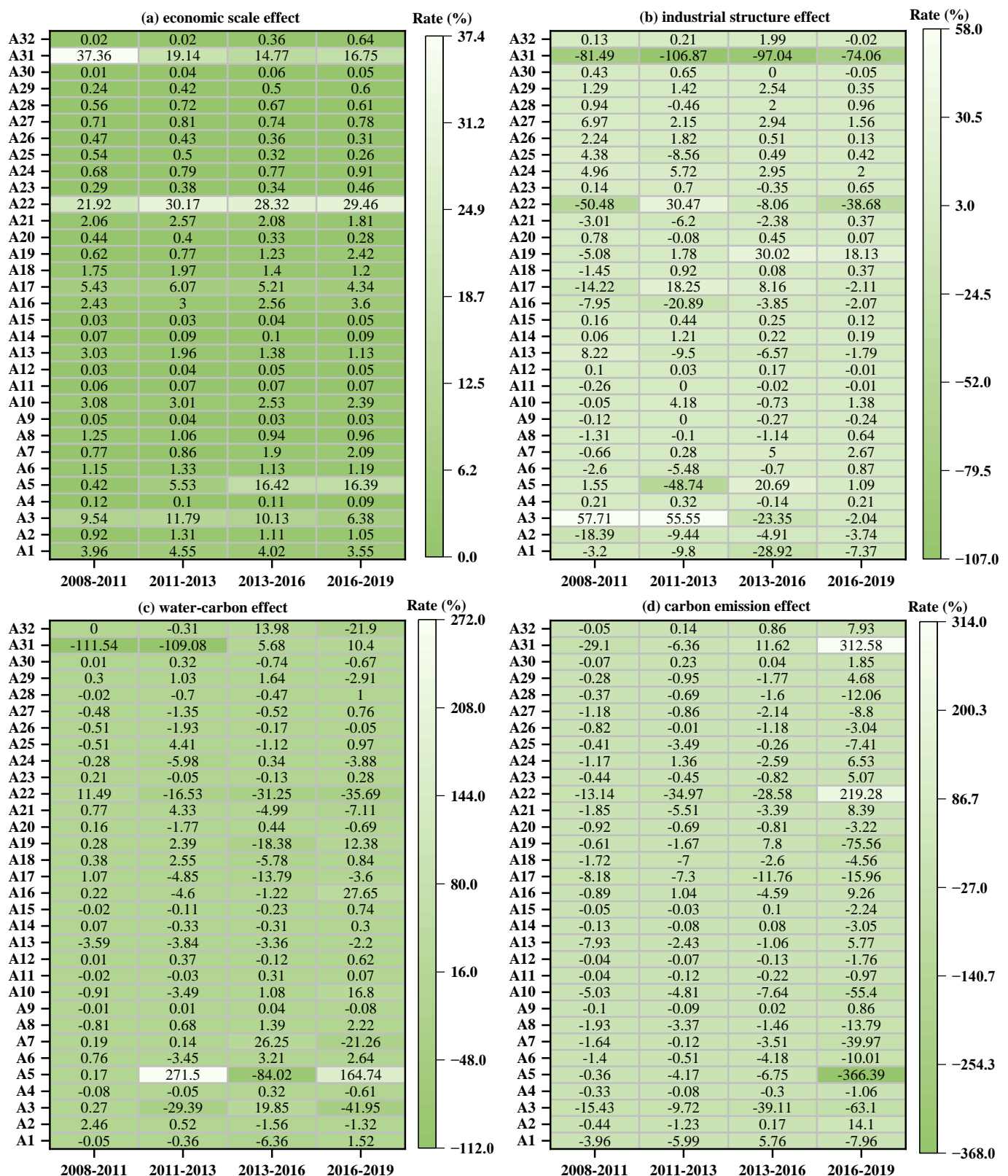
(a) economic scale effect

	2008-2011	2011-2013	2013-2016	2016-2019
A32	0.02	0.02	0.36	0.64
A31	37.36	19.14	14.77	16.75
A30	0.01	0.04	0.06	0.05
A29	0.24	0.42	0.5	0.6
A28	0.56	0.72	0.67	0.61
A27	0.71	0.81	0.74	0.78
A26	0.47	0.43	0.36	0.31
A25	0.54	0.5	0.32	0.26
A24	0.68	0.79	0.77	0.91
A23	0.29	0.38	0.34	0.46
A22	21.92	30.17	28.32	29.46
A21	2.06	2.57	2.08	1.81
A20	0.44	0.4	0.33	0.28
A19	0.62	0.77	1.23	2.42
A18	1.75	1.97	1.4	1.2
A17	5.43	6.07	5.21	4.34
A16	2.43	3	2.56	3.6
A15	0.03	0.03	0.04	0.05
A14	0.07	0.09	0.1	0.09
A13	3.03	1.96	1.38	1.13
A12	0.03	0.04	0.05	0.05
A11	0.06	0.07	0.07	0.07
A10	3.08	3.01	2.53	2.39
A9	0.05	0.04	0.03	0.03
A8	1.25	1.06	0.94	0.96
A7	0.77	0.86	1.9	2.09
A6	1.15	1.33	1.13	1.19
A5	0.42	5.53	16.42	16.39
A4	0.12	0.1	0.11	0.09
A3	9.54	11.79	10.13	6.38
A2	0.92	1.31	1.11	1.05
A1	3.96	4.55	4.02	3.55

Rate (%): 37.4 / 31.2 / 24.9 / 18.7 / 12.5 / 6.2 / 0.0

(b) industrial structure effect

	2008-2011	2011-2013	2013-2016	2016-2019
A32	0.13	0.21	1.99	-0.02
A31	-81.49	-106.87	-97.04	-74.06
A30	0.43	0.65	0	-0.05
A29	1.29	1.42	2.54	0.35
A28	0.94	-0.46	2	0.96
A27	6.97	2.15	2.94	1.56
A26	2.24	1.82	0.51	0.13
A25	4.38	-8.56	0.49	0.42
A24	4.96	5.72	2.95	2
A23	0.14	0.7	-0.35	0.65
A22	-50.48	30.47	-8.06	-38.68
A21	-3.01	-6.2	-2.38	0.37
A20	0.78	-0.08	0.45	0.07
A19	-5.08	1.78	30.02	18.13
A18	-1.45	0.92	0.08	0.37
A17	-14.22	18.25	8.16	-2.11
A16	-7.95	-20.89	-3.85	-2.07
A15	0.16	0.44	0.25	0.12
A14	0.06	1.21	0.22	0.19
A13	8.22	-9.5	-6.57	-1.79
A12	0.1	0.03	0.17	-0.01
A11	-0.26	0	-0.02	-0.01
A10	-0.05	4.18	-0.73	1.38
A9	-0.12	0	-0.27	-0.24
A8	-1.31	-0.1	-1.14	0.64
A7	-0.66	0.28	5	2.67
A6	-2.6	-5.48	-0.7	0.87
A5	1.55	-48.74	20.69	1.09
A4	0.21	0.32	-0.14	0.21
A3	57.71	55.55	-23.35	-2.04
A2	-18.39	-9.44	-4.91	-3.74
A1	-3.2	-9.8	-28.92	-7.37

Rate (%): 58.0 / 30.5 / 3.0 / -24.5 / -52.0 / -79.5 / -107.0

(c) water-carbon effect

	2008-2011	2011-2013	2013-2016	2016-2019
A32	0	-0.31	13.98	-21.9
A31	-111.54	-109.08	5.68	10.4
A30	0.01	0.32	-0.74	-0.67
A29	0.3	1.03	1.64	-2.91
A28	-0.02	-0.7	-0.47	1
A27	-0.48	-1.35	-0.52	0.76
A26	-0.51	-1.93	-0.17	-0.05
A25	-0.51	4.41	-1.12	0.97
A24	-0.28	-5.98	0.34	-3.88
A23	0.21	-0.05	-0.13	0.28
A22	11.49	-16.53	-31.25	-35.69
A21	0.77	4.33	-4.99	-7.11
A20	0.16	-1.77	0.44	-0.69
A19	0.28	2.39	-18.38	12.38
A18	0.38	2.55	-5.78	0.84
A17	1.07	-4.85	-13.79	-3.6
A16	0.22	-4.6	-1.22	27.65
A15	-0.02	-0.11	-0.23	0.74
A14	0.07	-0.33	-0.31	0.3
A13	-3.59	-3.84	-3.36	-2.2
A12	0.01	0.37	-0.12	0.62
A11	-0.02	-0.03	0.31	0.07
A10	-0.91	-3.49	1.08	16.8
A9	-0.01	0.01	0.04	-0.08
A8	-0.81	0.68	1.39	2.22
A7	0.19	0.14	26.25	-21.26
A6	0.76	-3.45	3.21	2.64
A5	0.17	271.5	-84.02	164.74
A4	-0.08	-0.05	0.32	-0.61
A3	0.27	-29.39	19.85	-41.95
A2	2.46	0.52	-1.56	-1.32
A1	-0.05	-0.36	-6.36	1.52

Rate (%): 272.0 / 208.0 / 144.0 / 80.0 / 16.0 / -48.0 / -112.0

(d) carbon emission effect

	2008-2011	2011-2013	2013-2016	2016-2019
A32	-0.05	0.14	0.86	7.93
A31	-29.1	-6.36	11.62	312.58
A30	-0.07	0.23	0.04	1.85
A29	-0.28	-0.95	-1.77	4.68
A28	-0.37	-0.69	-1.6	-12.06
A27	-1.18	-0.86	-2.14	-8.8
A26	-0.82	-0.01	-1.18	-3.04
A25	-0.41	-3.49	-0.26	-7.41
A24	-1.17	1.36	-2.59	6.53
A23	-0.44	-0.45	-0.82	5.07
A22	-13.14	-34.97	-28.58	219.28
A21	-1.85	-5.51	-3.39	8.39
A20	-0.92	-0.69	-0.81	-3.22
A19	-0.61	-1.67	7.8	-75.56
A18	-1.72	-7	-2.6	-4.56
A17	-8.18	-7.3	-11.76	-15.96
A16	-0.89	1.04	-4.59	9.26
A15	-0.05	-0.03	0.1	-2.24
A14	-0.13	-0.08	0.08	-3.05
A13	-7.93	-2.43	-1.06	5.77
A12	-0.04	-0.07	-0.13	-1.76
A11	-0.04	-0.12	-0.22	-0.97
A10	-5.03	-4.81	-7.64	-55.4
A9	-0.1	-0.09	0.02	0.86
A8	-1.93	-3.37	-1.46	-13.79
A7	-1.64	-0.12	-3.51	-39.97
A6	-1.4	-0.51	-4.18	-10.01
A5	-0.36	-4.17	-6.75	-366.39
A4	-0.33	-0.08	-0.3	-1.06
A3	-15.43	-9.72	-39.11	-63.1
A2	-0.44	-1.23	0.17	14.1
A1	-3.96	-5.99	5.76	-7.96

Rate (%): 314.0 / 200.3 / 86.7 / -27.0 / -140.7 / -254.3 / -368.0

Figure 11. Changes in the contributions of the factors in the different periods.

4.2.4. Water–Carbon Effect

As shown in Figures 11 and 13, the water–carbon effect was unstable between the sectors, with more drastic changes in individual sectors. In particular, the production and supply of electricity and heat power sector (A31) exhibited the greatest change in the

technology effect, changing from negative to positive values. Its contribution changed from −111.54% to 10.40%. The ferrous metal smelting and rolling processing sector (A22) exhibited the next greatest change (from 11.49% to 35.69%). The more water-intensive industries had positive water–carbon effects, mainly including the food industries (A6, A7, and A8), the textile sector (A10), and the petroleum processing, coking, and nuclear fuel processing sector (A16). The water–carbon factors of these industries increased, which contributed to the growth of the water use. The same change occurred in the non-metallic mining and processing sector (A5). The water–carbon nexus was directly related to the water use and carbon emissions. When the carbon emissions decreased and the water use increased, the water–carbon factor increased, such as in the food manufacturing industry (A7); however, when the decrease in the carbon emissions was less than the reduction in the water use, the water–carbon factor increased, such as in the wine, beverage, and refined tea manufacturing industry (A8). Therefore, carbon reduction and water conservation efforts should be coordinated, and one cannot be achieved without the other.
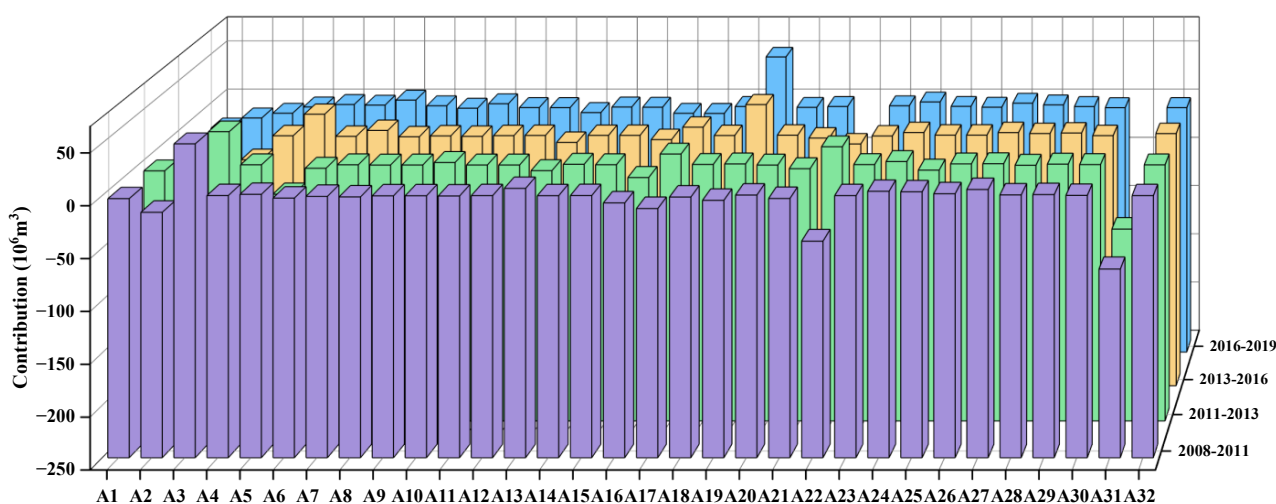
Figure 12. Industrial structure effects of changes in water use by sector.
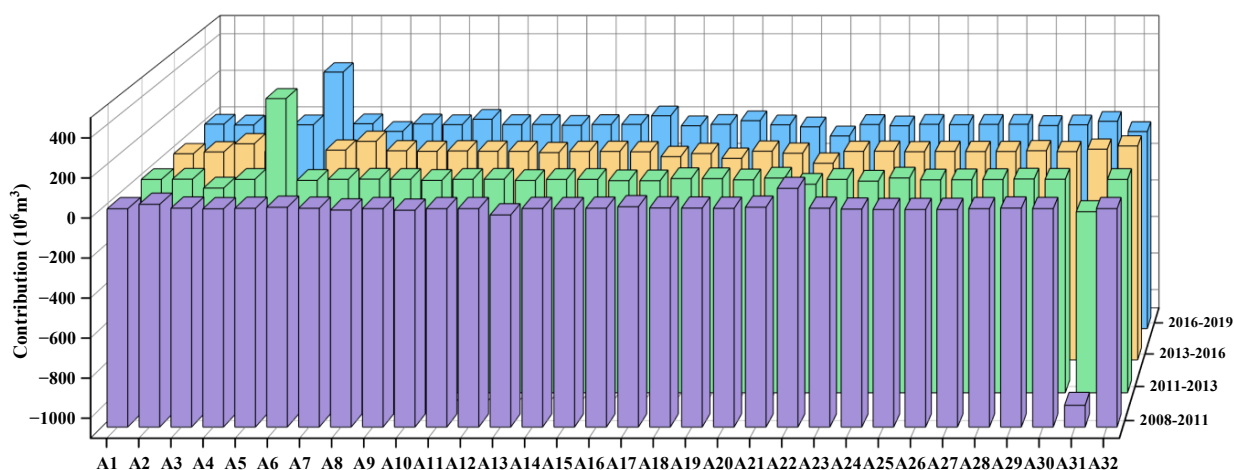
Figure 13. Water–carbon effect of changes in water use by sector.

4.2.5. Carbon Emission Effect

As can be seen from Figures 11 and 14, the number of industries with positive carbon emission effects gradually increased, indicating that the inhibiting effect of the carbon emission effect on water use gradually decreased. From 2008 to 2011, the water use of the production and supply of electric power and heat power sector (A31) decreased by 228.27 million m^3, with a contribution of −29.10%. This was the main industry in terms of water use reduction. However, after 2013, the carbon effect became positive. It seems to

have reached the limit of its carbon emission efficiency. In addition, there were positive and negative alternations in the ferrous metal smelting and rolling processing sector (A22) and the petroleum processing, coking, and nuclear fuel processing sector (A16). The ferrous metal smelting and rolling processing sector (A22) was the first to increase and then decrease, and it seems that there is less room to improve its carbon emission efficiency. However, the petroleum processing, coking, and nuclear fuel processing sector (A16) made the largest contribution to the water use reduction (−4.59%), and there was a great deal of room for improvement in its carbon emission efficiency. In addition, the carbon emission effects of some sectors gradually increased their inhibiting effect on the growth of water use (e.g., A1, A6, A7, A8, A10, A17, A19, and A20).
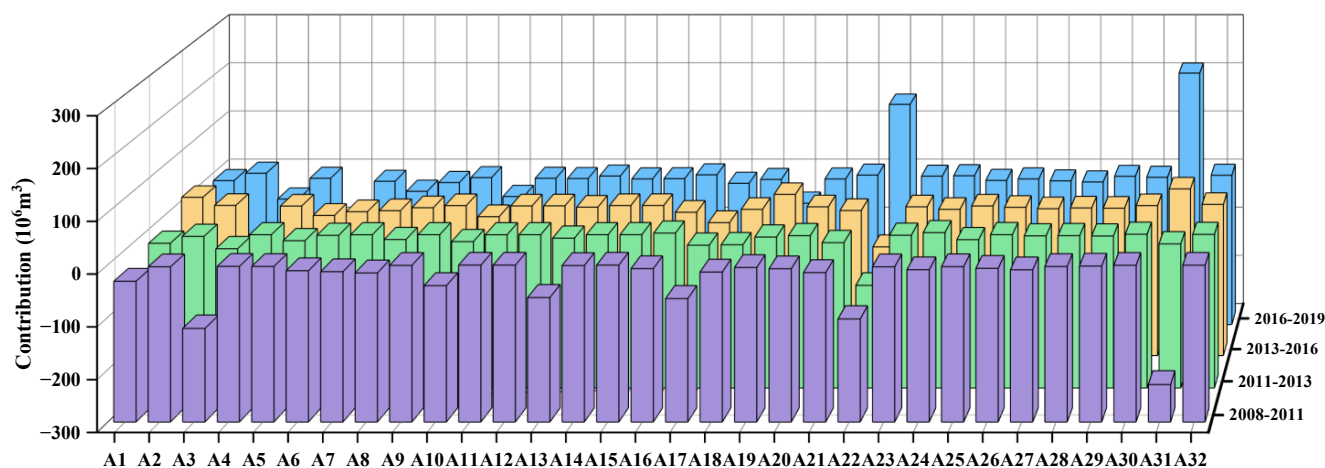
Figure 14. Carbon emission effect of changes in water use by sector.

4.3. Major Industries

By analyzing the driving factors of each industrial sector, the different industries were classified into four types based on the total effect of each industry [35]: strongly promoting industries, weakly promoting industries, strongly inhibiting industries, and weakly inhibiting industries. The strongly promoting and inhibiting industries and their main driving factors of industrial water use change in Hebei Province are shown in Table 2. The total of 1254.72 million m^3 of water use reduction was driven by the strongly inhibiting industries, which was almost equal to the 1265.47 million m^3 reduction by all the inhibiting industries. The increase in water use driven by the strongly promoting sectors was 760.31 million m^3, which was almost equal to the total increase. This shows that the strongly promoting and strongly inhibiting industries were the primary industries that affected the change in the industrial water use and are the industries that need to be focused on in industrial water conservation construction and management in Hebei Province.

In terms of the main influencing factors, the carbon emission effect was the main inhibiting factor, while the water–carbon effect and the industrial structure effect were the second most important. The strongly inhibiting and strongly promoting industries were mainly high carbon and high water consumption industries, and they were the main industries leading to the change in industrial water consumption in recent years. This indicates that industries with high carbon emissions require large amounts of water consumption. From the previous sectoral analysis, it is possible to consider reducing carbon emissions and improving carbon efficiency in terms of structural adjustment, thus improving the water efficiency and further saving industrial water. For example, the chemical raw materials and chemical products manufacturing sector (A17) should pay attention to the inhibiting effect of the structural effects, and it can optimize the industrial structure with water and carbon saving as constraints. For industries with dominant carbon emission efficiency effects, emission reduction and water conservation management should be considered. The key driver of the strongly promoting industries was the economic effect. In this regard, the scale of its development should be gradually restricted, and the

proportion of these industries should be adjusted to slow down the increase in the pressure of industrial water use. By analyzing the drivers of the strongly promoting industries, key factors can be effectively identified and corresponding measures can be formulated. For example, the petroleum processing, coking, and nuclear fuel processing sector (A16) should focus on improving water use efficiency, while the chemical fiber manufacturing industry (A19) should pay attention to structural adjustment.

Table 2. Industry classification and driving factors in Hebei Province.

Type	Code	Economic Scale Effect	Industrial Structure Effect	Water–Carbon Effect	Carbon Emission Effect
Strongly inhibition	A31		√ (−90.89%)	√√ (−120.95%)	
	A3			√ (−66.34%)	√√ (−187.98%)
	A13		√ (−31.92%)	√ (−67.87%)	√√ (−69.93%)
	A17			√ (−74.81%)	√√ (−287.27%)
	A10				√√ (−473.71%)
	A1		√√ (−314.12%)	√ (−53.01%)	√ (−185.77%)
	A8				√√ (−312.50%)
	A18			√ (−47.39%)	√√ (−415.72%)
	A26			√ (−111.06%)	√√ (−184.49%)
	A25				√√ (−264.16%)
Strongly promotion	A5	× (25.79%)		×× (105.20%)	
	A22	×× (212.94%)			
	A16	×× (124.04%)		× (61.34%)	
	A19	× (65.50%)	×× (121.59%)		
	A29	×× (78.57%)	× (47.28%)	× (44.94%)	
	A23	×× (117.11%)	× (24.52%)	× (34.08%)	
	A24	×× (269.13%)	× (252.73%)		
	A2	××× (265.72%)		×× (226.25%)	× (41.47%)
	A7	××× (520.36%)	× (138.73%)	×× (272.85%)	
	A6	×× (646.26%)		× (322.76%)	

Notes: "√√" denotes the dominant inhibiting factor, and "√" denotes the secondary inhibiting factor. "××" denotes the dominant promoting factor, and "×" denotes the secondary promoting factor. The numbers in parentheses represent the extent to which each factor contributed to the change in the water use in the sector.

5. Discussion

In this paper, the industrial water efficiency was decomposed into the carbon emission efficiency and water–carbon relationship factor, and the sum of these two factors demonstrated that improving the carbon emission efficiency and improving the water–carbon relationship can improve the industrial water use efficiency. Therefore, controlling carbon emissions can significantly curb the growth of industrial water use. This result is supported by the findings of Su et al. [36]. However, Ji et al. [37] found that the economic output benefits of water use can curb the growth of carbon emissions. This can be compared with the results of this study to show that industrial water use and carbon emissions are mutually influential. Currently, carbon emissions are being reduced through technological advances to improve energy efficiency. There is also a reduction of carbon emissions through industrial restructuring. Su et al. [36] suggested optimizing the industrial structure by limiting high carbon and high water consumption industries. However, the goal of industrial restructuring is not only water saving [38], and carbon reduction is also one of its goals. Some researchers have concluded that the water use efficiency factor [14] and the industrial structure factor [30] are the factors that contribute to the inhibition of the increase in industrial water use, while the economic scale factor [19] is the promoting factor, which is consistent with the conclusions of this study.

The decomposition results of this study show that the contribution of Hebei's industrial structure effect to curbing the industrial water use is still relatively small, and the industrial structure effect is not fully effective. Li et al. [8] found that the industrial restructuring in

Hebei Province has a significant water-saving potential. Shang et al. [38] found that water conservation-oriented industrial restructuring in Tianjin should focus on sectors A22 and A21. However, in this study, it was found that sectors A16, A17, and A19 should also be focused on. In addition, by decomposing the results for the industries, it was found that the water use of the sectors is heterogeneous. Various drivers played different roles in the different sectors, resulting in great heterogeneity in the water use of the different sectors. For example, compared with sector A31, the structural effect of sector A5 was less inhibited and the water–carbon relationship was not coordinated, resulting in increased water use in sector A5. The different industries should take targeted measures to adjust their water use.

Compared with existing methods, the LMDI method can quantify the degree to which the carbon emissions, industrial economic scale, and industrial structure affect industrial water use. This method also provides a new tool for analyzing water–carbon relationships. If sufficient data are available, this method is also applicable to the analysis of water–carbon or water–energy relationships in other regions. Based on the additivity of regional water use, the method can also be applied to multiple regions simultaneously to analyze the impact of water use in different subregions on the entire region. In this study, the impact of industrial carbon emissions on industrial water use was quantified, but no deeper link was found between them, which will be the focus of further research.

6. Conclusions

Based on the analysis of the current situation of the water resources and industrial structure in Hebei Province, in this study, the factors of the industrial water use during 2008–2019 were decomposed using the LMDI model and the contributions of the driving factors were quantitatively assessed. The following conclusions were drawn. Overall, the industrial water consumption in Hebei Province decreased during 2008–2019, but the rate of decrease gradually slowed down. The economic effect was the contributing factor, with a cumulative contribution of 446.23% during 2008–2019. However, the carbon emission effect (−286.11%), the water–carbon effect (−153.19%), and the industrial structure effect (−106.93%) were the main factors responsible for the decrease in the industrial water use.

Based on the results of the sectoral decomposition, the expansion of the economic scales of the different industries promoted the growth of industrial water use to different degrees. For example, the water use of sectors A31 and A30 increased by 774.93 and 0.55 million m^3, respectively. In addition, although industrial restructuring had a great potential to reduce water use, the industrial structure effect was uncertain and unstable, and the industrial structure effect was highly variable in some industries. The deteriorating water–carbon relationship promoted the growth of industrial water use, and carbon reduction and water conservation should be coordinated and synchronized. The industries with high carbon emissions also used more water. The improvement of the carbon emission efficiency and water–carbon relationship can increase industrial consumption and thus reduce the industrial water demand. The results of the sectoral decomposition show that the high water use industries had the greatest impact on the industrial water use (−171.14%). In addition, the carbon emissions effect of each industry made a significant contribution to the industrial water demand. The strongly promoting sectors (A5, A22, A16, A19, A23, A24, A2, A7, and A6) were the ten most relevant contributing sectors to the increase in industrial water use, with a combined contribution of 760.31 million m^3 during 2008–2019.

Based on the above decomposition results, the changes in the water use and the driving forces in the different sectors were not consistent. Based on this, we propose several policy recommendations. First, attention should be paid to the research and development of water-saving technologies in low water efficiency sectors, and the carbon emission efficiency should be improved to reduce water consumption. These sectors (including A2, A5, A16, and A32) have a low water–carbon relationship, as well as a low carbon emission efficiency, and are also high water consumption sectors, so their water consumption should be reduced by accelerating technological progress oriented toward water and carbon saving, and more resources should be invested in research and development to improve production

technology. Second, the structure of the industrial water use should be optimized and an industrial structure that is compatible with the carrying capacity of the water resources should be achieved. These sectors (e.g., A22, A2, A19, and A16) should adjust their industrial structure, accelerate the upgrading of high water-consuming industries, and reduce the proportion of high water consumption industries, i.e., reducing and eliminating high water-consuming industries with an excess capacity, such as the iron and steel and petrochemical industries. Combined with the current strategic opportunity for synergistic development in the Beijing–Tianjin–Hebei region, Hebei Province should introduce and develop low water consumption and high value-added industries. Finally, compared with reducing the economic scale of these sectors (e.g., A3, A22, and A31), it is more important to improve their water efficiency via measures such as increasing low-carbon technology innovation and investment in the renovation of water-saving equipment.

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